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FINITE ELEMENT WELDING COMPUTATIONS USING GENERAL PURPOSE NONLINEAR ANALYSIS CODES

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Parts being welded experience high local temperatures and severe thermal gradients which lead to large local stresses due to nonuniform thermal expansion and contraction. Unacceptable degradation of material mechanical properties, residual stresses, and changes in geometry can result. General purpose nonlinear finite element method analysis codes offer features which should facilitate their use for predicting welding temperatures, displacements, and stresses. A series of computations evaluating the use of general purpose codes for this purpose is described. Useful code features are identified and computational procedures to enhance solution accuracy suggested.

INTRODUCTION

Welding processes use intense local heating to form a region of molten material, the weld pool, in parts being joined. The bond between the parts is formed by solidification of the weld pool.

Mechanical properties of the solidified weld pool material are strongly influenced by temperatures experienced during welding. Material in the adjacent heat affected zone is also heated enough to significantly affect its mechanical properties. Properties in the solidified weld pool and heat affected zone may be quite different after welding from pre-welding properties.

The intense local heating used to form the weld pool produces transient heat affected zone temperatures approaching the material melting point and severe thermal gradients through much of the weld vicinity. Nonuniform expansion and contraction due to the thermal gradients result in large local stresses which frequently lead to plastic material behavior. Residual stresses are then left in the welded material following cooling and residual displacements which alter weld geometry are produced.

The design of a satisfactory welded joint can be a formidable task. Enough heat must be applied to form an adequate bond, but unacceptable degradation of material properties, residual stresses, and changes in weld geometry avoided. An emperical approach based on experience and trial and error is usually followed. Continued progress in finite element method (FEM) prediction of welding temperatures, stresses, and displacements promises, however, to support analysis based weld joint design in the not too distant future.

The physical complexity of welding processes presents a number of computational difficulties to welding analyses. The processes are nonsteady state and require transient analyses beginning at the initiation of heating and continuing until cooling is essentially complete. Welding geometries are almost always three dimensional and two dimensional analyses can only describe them approximately. The large temperature variations and strains which occur during welding make welding analyses inherently nonlinear. Filler metal addition introduces an additional computational difficulty for many welding processes.

Temperatures experienced during welding range from ambient to well above material melting points. They necessitate the treatment of material thermal and mechanical properties as temperature dependent. Heats of fusion associated with melting and solidification and heats of transformation associated with solid phase changes must be included in analyses. Conduction heat transfer occurs throughout parts being welded. Other important heat transfer mechanisms may include convection through the molten weld pool and radiation, convection, and weld pool vaporization heat losses to surroundings.

Stress and displacement predictions require the consideration of plastic material behavior and strain hardening. Creep may be important, particularly if the effects of post weld heat treatments are to be investigated. Stresses and displacements may be affected by density changes associated with solid phase changes and analyses should reflect this. Nonreversible temperature induced changes in material crystal structure may make consideration of temperature history dependent material mechanical properties desirable. Material melting and/or recrystalization anneal away accumulated elastic and plastic strains and change local undeformed configurations for weld pool and heat affected zone material. Significant effects on displacements and stresses occur and should be included in analyses.

Hibbitt and Marcal (1) pioneered the applications of FEM analysis to welding processes. Other early FEM welding analyses were carried out by Nickell and Hibbitt (2), Muraki, Bryan, and Masubuchi (3), and Friedman (4) (5). Goldak, Patel, Bibby, and Moore (6) (7) recently described the current state-of-the-art in FEM welding analyses and cited many of those who have contributed to its development. Cacciatore (8) described the development of the state-of-the-art in numerical, including FEM, welding heat transfer analysis.

Early published FEM welding analyses, and most of those which have followed, used computer codes specifically developed to study welding. Code features treating various physical phenomena have been implemented as necessary to investigate particular welding processes, i.e. gas tungsten arc (GTA) welding, or particular aspects of welding processes, i.e. the effects of solid phase transformations on residual stresses. The codes are usually not widely distributed and each group of welding researchers tends to develop and use its own.

General purpose nonlinear FEM analysis codes have benefitted from long periods of continued development and are widely distributed. They offer many features which facilitate welding analyses. Among these features are temperature dependent material properties and heat of fusion and transformation effects, stable, computationally efficient solution procedures for describing highly nonlinear transient phenomena, plasticity and creep models, coupled temperature and displacement-stress solution techniques, and flux, radiation, and convection thermal boundary conditions. Temperature history dependent material models and the ability to readily describe melting or recrystalization annealing away of accumulated strains are desirable features not usually implemented at present in general purpose codes.

De Young and Chiu (9) presented an early application of a general purpose FEM code to predict welding temperatures. Nied (10) and Herrera (11) have published descriptions of recent predictions of welding temperatures, displacements, and stresses using general purpose codes. Duncan (12) carried out a detailed investigation of the suitability of a set of general purpose coupled thermal, stress-displacement FEM codes for welding analysis and noted the lack of ability to model temperature history dependent material behavior as a significant code limitations for this purpose. Papazoglu (13) and Papazoglu and Masubuchi (14) described modifications of a general purpose code to include transformation strains and melting induced plastic strain relief effects on residual stress and displacement predictions. Shapiro and Mahin (15) described modifications of a general purpose heat transfer code to describe weld pool vaporization heat losses.

This paper presents a series of computations which investigated several aspects of the use of general purpose nonlinear FEM analysis codes for describing welding processes. Computed temperatures and displacements are compared to data measured during a simple welding experiment. Code characteristics which facilitate welding analysis are identified. User implemented modeling techniques, including the appropriate specification of high temperature material properties which enhance the accuracy of stress-displacement predictions, are discussed. Recommendations for future code enhancements are made.

GENERAL DESCRIPTION OF COMPUTATIONS

Computations describe a simple, well characterized, welding experiment carried out by Duncan specifically to furnish data for evaluating FEM code suitability for welding analysis (12). He made a 200 amp, 2.1 second duration, gas tungsten arc (GTA) spot weld at the center of a 76.2 mm. (3 inch) diameter, 4.76 mm. (3/16 inch) thick, circular nickle plate, Figure 1. Thermocouple temperature measurements were made at four locations on the plate and weld pool decay following flux termination observed and recorded. Transient displacements were recorded at two locations on the bottom of the plate.

Duncan's welding experiment is well suited for its intended purpose of FEM code evaluation. The simple axisymmetric plate geometry is two dimensional and avoids errors introduced when two dimensional analyses are used to describe three dimensional welds. The simple axisymmetric finite element meshes which can be used to describe the experiment are easily generated and input heat flux and radiation and convection boundary conditions easily specified. The meshes contain relatively few nodes and elements, minimizing FEM analysis computer run times and facilitating parametric series of computations investigating the effects of changes in computational procedures or modeling details. Welding a pure nickel plate eliminated the effects of solid phase change associated heats of transformation and density changes from experimental results and avoided related computational difficulties. No filler metal was introduced during the weld, avoiding another computational difficulty.

The highly localized stresses and strains existing in and near weld pools are very difficult to measure on either a time dependent or residual basis. Although recent developments (16) (17) promise to make possible at least residual measurements in the weld pool and its vicinity, presently only measurements at locations somewhat distant from the weld pool are made. It is at these locations that computed strains are usually compared to measured values in evaluating welding analyses. Unfortunately the strains which are compared are much less sensitive to variations in computational procedures and modeling techniques than are strains in and near the weld pool and the value of the comparisons is much reduced. Lack of stress or strain data from Duncan's experiment does not seriously limit the experiment's value for evaluating FEM welding analysis procedures given present state-of-the-art limitations on ability to obtain data which would support meaningful comparisons.

Computations were carried out with general purpose FEM analysis code ABAQUS (18). Code features used include automatic incrementation control with iteration and sequentially coupled temperature and stress-displacement analysis.

Welding processes involve strongly coupled displacements and temperatures. The relatively small amount of heat generated by welding deformations makes the coupling unidirectional with welding temperatures essentially independent of displacements except for those welding processes in which heat flow is displacement dependent.

Few published welding analyses have used a fully coupled temperature displacement analysis procedure. Almost all have used a sequentially coupled procedure with temperatures calculated first and then used as input for stress-displacement calculations. Nied's analysis of spot welding (10) for which workpiece and electrode deformations determine contact areas for electric current and heat flows and strongly influence temperatures is a notable exception.

Sequentially coupled analysis procedures can accurately describe most welding processes and make it possible to first complete temperature calculations and then concentrate on the more difficult and computer time intensive stress-displacement computations. Care must be taken, however, when using a sequentially coupled procedure to insure that computed temperatures are correctly stored and transferred to subsequent displacement computations.

A sequentially coupled analysis procedure was used in this study.

THERMAL COMPUTATIONS

The accurate computation of welding temperatures requires that limitations of available high temperature material thermal property data, input heat flux data, and basic understanding of welding related heat transfer phenomena be overcome (12). Material property data required for welding heat transfer analyses includes coefficient of conduction and specific heat values for temperatures ranging from ambient up to the maximum temperature likely to be experienced in the molten weld pool. High temperature data is often not available and must be estimated. Input welding heat fluxes are difficult to characterize. Their time dependence and spatial distribution must be approximated using simplified physical models and experimentally based emperical corrections. Although progress is being made in developing a fundamental understanding of weld pool convection heat transfer and weld pool vaporization heat losses (19) - (21), these phenomena are still not amenable to analytical description as a part of welding temperature computations. Their effects are emperically included in computations through the use of artificially enhanced coefficients of conduction for molten material and adjustments to input heat flux descriptions.

Nickel conductivity and specific heat values used in the temperature computations are shown in pressented in Table I. The large increase in conductivity for temperatures above 1750°k represents the artificial enhancement recommended by Duncan based on experience with similar welding processes to approximate the effects of weld pool convection. A 4.32×10^5 Joule /kg. nickel latent heat of fusion was directly incorporated in the analysis. Ambient density was specified as 8.58×10^3 kg/m^3.

The spatial variation of the GTA generated heat flux applied to the upper surface of the plate is described by Figure 2. Flux time dependence is included in the analysis by multiplying flux values from Figure 2 by the time dependent scale factor from Figure 3. Linear flux decay to zero over a .1 second duration time interval following arc termination at 2.1 seconds was assumed.

Radiation and convection heat losses from the plate to its surroundings occur during the welding experiments. An emissivity of .5 and surroundings at 294°k were assumed in describing radiation losses. Convections losses were considered unimportant during the time period of interest and were ignored.

The axisymmetric finite element model shown in Figure 4 was used for the computations. The plate is modeled with 656 nodes and 600 axisymmetric four node heat transfer elements. A fine mesh is used near the center of the plate where severe thermal gradients are expected and a coarser mesh outside this region.

Boundary conditions specifying radiation heat loss to blackbody surroundings were prescribed on the outer faces of elements on the upper and lower surfaces of the finite element model. Procedures for directly specifying the radiation boundary conditions proved to be preferable to indirect procedures sometimes used. Indirect procedures require user definition of radiation link elements connecting exterior surface nodes to fixed temperature nodes representing the surface's surroundings.

They may also require manual user calculations and input of an effective cross sectional area for each radiation link element. This tedious and time consuming process is avoided by direct specification.

Prescribed element surface heat fluxes describe the GTA weld flux applied to the FEM model. Flux time dependence was incorporated in the analysis using an input amplitude-time variation which was code applied to each of the element fluxes during computations. This combination of user specified element surface fluxes and amplitude-time variation was found to be very convenient.

Nodal heat fluxes are sometimes manually computed and input instead of element surface fluxes. This can be an unacceptably tedious and time consuming process for complex welding models. Flux time dependence is sometimes described by setting up a number of short solution time steps over which simple linear or constant flux time variations are assumed. The solution process can become awkward and overly complicated in comparison to use of directly specified flux amplitude time variation.

Transient nonlinear FEM welding temperature computations (and stress-displacement computations) use an incremental solution procedure. Temperature changes occurring during a small increment of time are computed and added to temperatures existing at the beginning of the increment to determine temperatures at the end of the increment. The process may be repeated on an iterative basis, applying corrections to temperature changes, until temperature convergence criteria are met. Temperatures at the end of the increment then serve as initial temperatures for the next increment and the solution procedure continued. Increment sizes can be chosen and input directly by the user, direct incrementation control, or selected automatically by a FEM code. automatic incrementation control, as part of a solution precedure.

Automatic incrementation control can be of significant assistance in minimizing computer run times while obtaining an accurate nonlinear FEM solution (22). Iterations within increments can contribute substantially to solution accuracy and to a stable, computationally efficient solution procedure. The user is still required, however, to specify appropriate values for accuracy and convergence criteria in order to make effective use of automatic incrementation control and iteration.

Automatic incrementation control with iteration was used throughout this study. A series of parametric computations was made to investigate the effects on computer run times and computed temperatures of changes in user specified values for the criteria, maximum allowable iterative temperature correction and incremental temperature change, and maximum and minimum allowable time increments, that control iteration and incrementation.

Solution accuracy was found to be little affected by criteria values, even when they were varied over a wide range. Smoothness of computed temperature-time solutions desired to obtain appropriate input for subsequent stress-displacement computations determined how tightly criteria had to be specified. Computer run times were strongly affected by criteria values. Run times over ten times longer than necessary resulted from specifying criteria too tightly. Expertise in choosing appropriate values for the criteria was quickly developed.

The temperatures which served as input to stress-displacement computations were computed using maximum allowable temperature change specified as 140°k°, maximum allowable temperature correction as 85°k, and maximum allowable increment size as .250 seconds. Eighty increments were used to describe 5.0 seconds of welding time and temperatures stored for stress-displacement computations at the end of each increment. Relatively small increments were chosen by the code during the first .5 seconds when rapid heating follows flux initiation and during the time from 2.1 seconds to 3.0 seconds immediately after flux termination. Increment sizes approaching the maximum allowable were used for the rest of the computations. Approximately 30 minutes of DEC VAX 8600 CPU time were required for the computations.

Temperatures computed at thermocouple locations are compared to measured temperatures in Figure 4. Predicted and measured weld pool decay are compared in Figure 5. Excellent agreement is seen to exist between measured and computed quantities. Differences between them are quite small, given uncertainties in material properties and weld flux time and spatial dependence, approximate emperical consideration of weld pool convection and vaporization, experimental errors in temperature and weld pool radius measurements, and discretization and numerical errors in the FEM calculations.

STRESS-DISPLACEMENT COMPUTATIONS

FEM welding stress-displacement computations treat all material, including molten weld pool material, as solid. The computations require specification of material mechanical properties including modulus of elasticity, Poisson's ratio, yield strength, tangent modulus, and coefficient of thermal expansion for all temperatures likely to be experienced. Mechanical properties emperically assigned to molten material reflect its liquid state. The high temperature properties needed for solid material near the melting point are difficult to measure and rarely available. They are emperically assigned as well.

High temperature liquid and solid material properties are usually assigned (1) (4) (13) in an attempt to reasonably approximate actual material behavior without introducing unacceptable computational difficulties. Low, but nonzero, values for liquid modulus of elasticity, tangent modulus, and yield strength are used in conjunction with liquid Poisson's ratio values approaching, but not equal to, .5. Property transitions from the highest temperature values available to assigned liquid values are assumed to take place in a physically reasonable fashion. An additional consideration used in this study in assigning high temperature mechanical properties is that of attempting to minimize solution errors introduced by limitations in FEM computational procedures.

Large strains accumulate in the molten weld pool. These strains do not, however, affect material behavior after cooling and solidification. The configuration of the weld pool as it solidifies becomes its new undeformed configuration from which displacements causing strains and stresses should be measured. Strains occurring prior to solidification are "forgotten" by the annealed weld pool material.

Elastic and plastic strains accumulate in the molten weld pool during finite element computations. They are usually retained in post solidification computations by general purpose analysis codes. The retained elastic strains cause the solidified weld pool to attempt to return to its preweld configuration. Retained plastic strains cause strain hardening of the solidified material. Annealing of the molten weld pool and redefinition of its undeformed configuration are not easily accomplished with most general purpose codes, adversely affecting computed residual displacements and stresses. Computations in this study investigated the use of material property definitions and special computational procedures to minimize these effects.

The finite element mesh used in heat transfer computations was used for stress-displacement computations as well. Element type was changed, of course, to reflect the change in dependent variables. Use of the same mesh allowed direct input of stored nodal temperatures to the stress-displacement analysis. The outer node on the lower surface of the plate was vertically restrained to prevent rigid body motion. Outer edges were radially unrestrained.

Preliminary stress-displacement computations encountered severe convergence difficulties with normal (displacement) elements. Computations terminated due to unsuccessful iteration, even with extremely small time increments, after describing approximately two seconds of weld time. Convergence difficulties and premature computation terminations continued even when physically unrealistic material properties were specified in an attempt to eliminate them. A change to hybrid (displacement and pressure) elements was necessary to improve convergence and continue preliminary computations to completion. Shortly after the change, a different integration algorithm was implemented in plasticity models in a later version of the code that provides much improved convergence, particularly for problems, which like welding problems, involve large plastic flows. Its use eliminated plasticity related convergence difficulties with displacement elements and they were used in all subsequent computations. This experience demonstrated the importance of code implemented stable, convergent solution algorithms.

Stress-displacement computations used automatic incrementation control, as did temperature computations. Time increments differed for the two types of analyses since they were determined by incrementation procedures controlled by different criteria. Code implemented interpolation automatically determined nodal temperatures at times required by stress-displacement computations.

The specification of material mechanical properties to minimize the effects of unrealistic weld pool strain retention was investigated in a parametric series of computations incorporating time independent plasticity. Mechanical property sets used, Table II, all specify the same modulus of elasticity and Poisson's ratio temperature dependence. They differ in elevated temperature yield strength and in ambient and elevated temperature strain hardening. Displacements computed using the four property sets are compared to measured displacements in Figures 7-10.

Property set 1 incorporates elevated temperature ratios of yield strength and tangent modulus equal to ambient temperature ratios. Significant strain hardening is specified at all temperatures. Displacements computed with these properties are seen to agree well with measured displacements until after flux termination at 2.1 seconds. They do not decay as rapidly after flux termination, however, as do measured displacements. This is particularly true for the displacement computed at a 12.76 mm radial distance from the plate center. It increases substantially after the measured displacement begin to decay and exhibits little decay afterward.

Limited agreement between computed and measured displacements after flux termination was attributed to the retention in post solidification FEM computations of elastic and plastic strains occurring in the molten weld pool. Property set 2 represents an attempt to improve agreement by minimizing the effects of these strains on computed displacements. Elevated temperature ratios of yield strength and tangent modulus are much less than ambient temperature ratios. Almost all high temperature strains are made plastic and elastic high temperature strains almost eliminated. Little strain hardening is incorporated at any temperature. Displacements computed with property set 2 display post flux termination decay very similar to that of measured displacements, supporting the assumption that strain hardening effects of retained strains had adversely affected previous post flux termination computations. Pre flux termination computed displacements are, however, seen to be significantly smaller than measured displacements.

Reintroducing strain hardening at lower temperatures to try to restore agreement between computed and measured pre flux termination displacements yielded property set 3. The reintroduction did not lead to larger pre flux termination displacements. It instead reduced computed post flux termination decay, adversely effecting agreement between computed and measured behavior.

Results obtained using property sets 1, 2, and 3 suggested that a material property set, set 4, combining the yield strength temperature dependence of set 1 and the minimal strain hardening of set 2 might enhance both pre and post flux termination agreement between computed and measured displacements. Excellent agreement is seen to result from computation using these properties.

Stresses and strains computed using the four sets of material properties were quite similar except near the center of weld. Computations using sets 2 and 4 predicted stresses and strains there considerably smaller than those predicted using sets 1 and 3. Differences between stresses and strains computed with the four property sets are almost certainly due to differences in specified strain hardening. No comparison of the relative accuracy of predicted stresses and strains is possible due to the lack of measured stress and strain data. Indeed, measurements of the highly localized strains near the center of the weld needed for a meaningful strain comparison would be difficult, if not impossible, given the current state-of-the-art in making such measurements. Fortunately, displacement comparison permits adequate evaluation of the computations.

Results obtained using the four property sets demonstrate the possibility of alleviating the effects on welding stress - displacement computations of unrealistic FEM weld pool strain retention by appropriate material property specification. Specification of minimal strain hardening and maintenance of a constant ratio of yield strength to elastic modulus throughout the temperature range, even if not in complete agreement with actual material behavior, may, for example, enhance accuracy of computed stresses and displacements. This technique is analagous to the emperical modification of weld pool coefficient of conduction to approximate weld pool convection on welding thermal analysis. Its effective use in describing a welding operation will similarly be dependent on user experience with similar operations.

The stress displacement computations just described were carried out in a computationally efficient manner with the use of automatic incrementation control and iteration. An appropriate value for the force tolerance measure controlling incrementation and iteration was readily determined by setting it to a small fraction of the maximum nodal force which would result if nodal constraints completely prevented element thermal expansion. As for temperature computations, specifications of the control too tightly was found to drastically increase computer run time without significantly affecting computed results. Approximately 60 time increments were required to describe 5.0 seconds of weld time with a reasonable force tolerance measure value and a minimum time increment of 1 second specified. Approximately 2.5 hours of VAX 8600 cpu time were required for a typical computation.

A series of computations investigating the capability to anneal away accumulated strains of a code implemented special computational procedure was also carried out. The procedure provides user controlled ability to remove elements during a computation and later replace them in an annealed state with previously accumulated plastic strains forgotten.

Element removal/replacement requires a multi-time step solution scheme. Groups of user designated elements can be removed or replaced during specified time steps. Incrementation and control criteria can be set differently for each of the time steps; as can the types of material behavior, i.e. time independent plasticity, creep, etc., described.

A four-time step solution scheme was set up to eliminate accumulated weld pool strains at flex termination. Computations began at weld flux initiation with a complete model. Elements known to be inside the weld pool from a review of computed temperatures were designated for removal during a short duration time interval following flux termination. They were replaced immediately afterward during a second short time interval. Computations with the complete model then continued to completion.

A review of computed results showed that accumulated plastic strains were indeed annealed away by the element removal/replacement procedure. They were immediately reintroduced into replaced weld pool elements, however, by existing displacements of nodes connected to adjacent elements. Undeformed configurations for replaced elements are determined by initial nodal locations. The "soft" molten replaced weld pool elements were immediately deformed to conform to deformed adjacent elements, reintroducing large strains into the molten weld pool. The reintroduced strains continued to adversely affect computed post flux termination displacements.

A modified element removal/replacement computational scheme was tried to avoid reintroduction of elastic and plastic strains into the weld pool. Drastically enhanced weld pool creep behavior was specified during element replacement so that strains would be reintroduced as creep strains instead. The creep strains would not adversely affect computed post flux termination displacements as the previously reintroduced strains had.

Partial success in reintroducing weld pool strains as creep strains was achieved. Unfortunately, creep related convergence difficulties led to unacceptably long computer run times. Continued efforts to reduce them through user specification of incrementation and control criteria were unsuccessful and effective use of element removal/replacement to improve the accuracy of post flux termination displacement computations prevented. The convergence difficulties may have been the result of details in the code creep implementation or of lack of user expertise in using the implementation effectively. The use of hybrid elements to improve creep convergence was not tried and might be worth investigation.

DISCUSSION AND CONCLUSIONS

The application of general purpose nonlinear FEM codes to welding analyses has been demonstrated and general purpose code capabilities facilitating the analyses identified.

Code ability to carry out welding analyses in a computationally efficient fashion is of primary importance. Solution algorithms providing accurate, convergent solutions for highly nonlinear welding problems involving large temperature changes, melting and solidification, and large plastic flows are essential. Convergence must not require unreasonably short time increments or excessive iteration.

Automatic incrementation control combined with iteration can be of significant assistance in minimizing computer run times while obtaining accurate welding solutions. Appropriate incrementation and iteration controls must be implemented and user ability to understand control criteria and select reasonable values for them supported.

Sequentially coupled solution procedures for temperature and stress displacement computations are preferred for most welding analyses not involving displacement dependent heat transfer. Code implemented procedures for easy storage and transfer of computed temperatures to stress-displacement computations are needed. Also needed are automatic interpolation procedures for determining nodal temperatures at times required by stress-displacement time incrementations.

Welding analysis set up can be made much easier by code provision of convenient procedures for thermal boundary condition and welding heat flux specification. Direct specification of element surface radiation heat loss to black body surroundings and element surface heat flux avoid indirect specification requiring tedious user calculations and input of radiation link elements and nodal heat flows. The provision of procedures for direct specification of arbitrary time dependence for welding heat fluxes can avoid awkward, unnecessarily complicated multi-time step solution schemes.

General purpose nonlinear FEM analysis codes do not usually provide users with the ability to readily anneal away accumulated strains in material which melts or undergoes recrystallization. The accuracy of welding stress-displacement computations can be adversely affected by unrealistic accumulated strain retention.

Appropriate emperical user specifications of material mechanical properties can reduce the adverse effects of unrealistic accumulated strain retention on solution accuracy. The maintenance of a constant ratio of yield strength to elastic modulus throughout the temperature range combined with the specification of minimal strain hardening appears promising, at least for welds similar to the one analyzed. User expertise in appropriate property specification for particular types of welds will depend on experience with similar welds, just as the ability to emperically include weld pool convection in thermal analyses through coefficient of conduction specification does.

Code implemented special computational features, such as element removal/replacement, may make it possible to reduce or eliminate the adverse effects of unrealistic accumulated strain retention on computed welding stresses and displacements. An in depth, code specific, investigation of special computational feature capability is required. Success in using such features to improve welding solutions accuracy may be limited by implementation details or lack of sufficient code specific user expertise.

Addition to general purpose nonlinear FEM codes of the ability to readily anneal away accumulated strains in material which melts or undergoes recrystallization would significantly enhance their value for welding analyses. Element removal/replacement, already implemented in some general purpose codes, would furnish this ability if two additional computational features were provided. Redefinition of the undeformed configuration for replaced elements based on the then current positions of nodes connected to adjacent elements would prevent the immediate reintroduction of large strains into replaced elements. Provision of an automatic procedure for element removal and replacement on the basis of element temperature would facilitate element by element treatment of annealing.

In conclusion, general purpose nonlinear FEM codes offer significant capability for welding analyses. Their capability in this area is somewhat limited, however, by lack of ability to easily describe annealing away of accumulated strains by melting or recrystallization. Appropriate user specification of material properties and/or already implemented special computational features may, at least partially, overcome this limitation. Code enhancements facilitating the treatment of annealing would increase code value for welding analyses.

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TABLE 1

Material Thermal Properties

Temperature (^oK)	Conductivity $\left(\frac{\text{Joules}}{\text{sec.m.k}^o}\right)$	Specific Heat $\left(\frac{\text{Joules}}{\text{kg.k}^o}\right)$
250	99.4	418.3
600	65.8	625.0
1700	86.7	625.0
1750	227.1	625.0
3000	227.1	625.0

TABLE 2

Material Mechanical Properties

(Properties Common to All Sets)

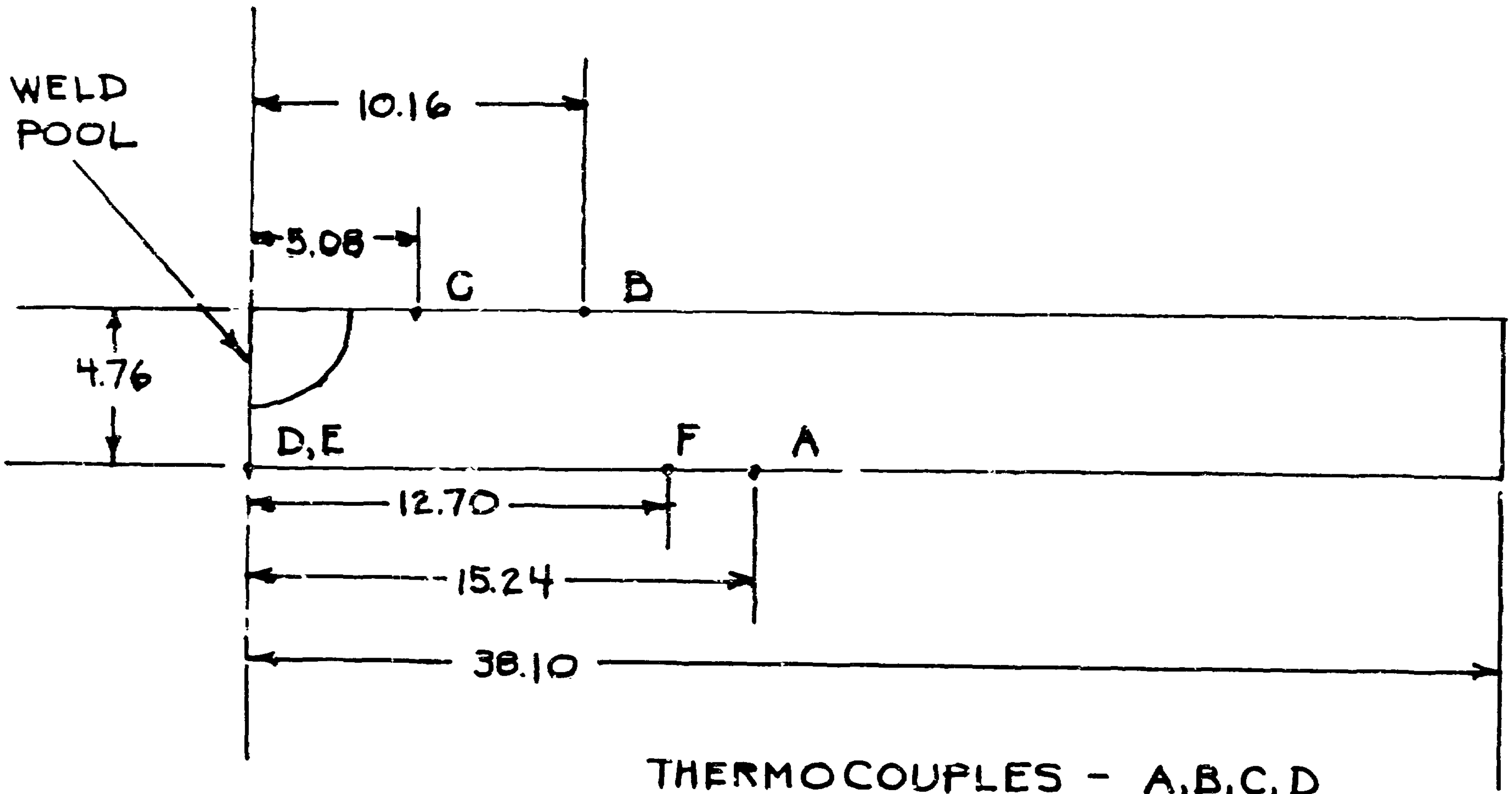
Temperature (^{o}k)	Modulus of Elasticity (GPa)	Poisson's Ratio	Coefficient of Thermal Expansion ($1/k^{o}$)
250	206.8	.3	1.271×10^{-5}
600	206.8	.8	1.541×10^{-5}
1100	103.7	.346	1.679×10^{-5}
1250	68.9	.361	1.679×10^{-5}
1800	.7	.45	1.679×10^{-5}
3000	.7	.45	1.679×10^{-5}

(Properties Differing from Set to Set)

	Set 1	Set 2	Set 3	Set 4
Yield Strength (MPa)				
250	158.6	158.6	158.6	158.6
600	158.6	158.6	158.6	158.6
1100	79.3	79.3	79.3	79.3
1250	52.9	.7	.7	52.9
1800	.5	7×10^{-3}	7×10^{-3}	.5
3000	.5	7×10^{-3}	7×10^{-3}	.5
Tangent Modulus (MPa)				
250	831.5	8.3	831.5	8.3
600	831.5	8.3	831.5	8.3
1100	417.4	4.1	417.4	4.1
1250	277.1	2.8	2.8	2.8
1800	2.8	2.8×10^{-2}	2.8×10^{-2}	2.8×10^{-2}
3000	2.8	2.8×10^{-2}	2.8x10-2	2.8×10^{-2}

FIGURE 1

PLATE WELDING EXPERIMENT



THERMOCOUPLES - A,B,C,D
DISPLACEMENT TRANSDUCERS - E,F

FIGURE 2
WELD HEAT FLUX

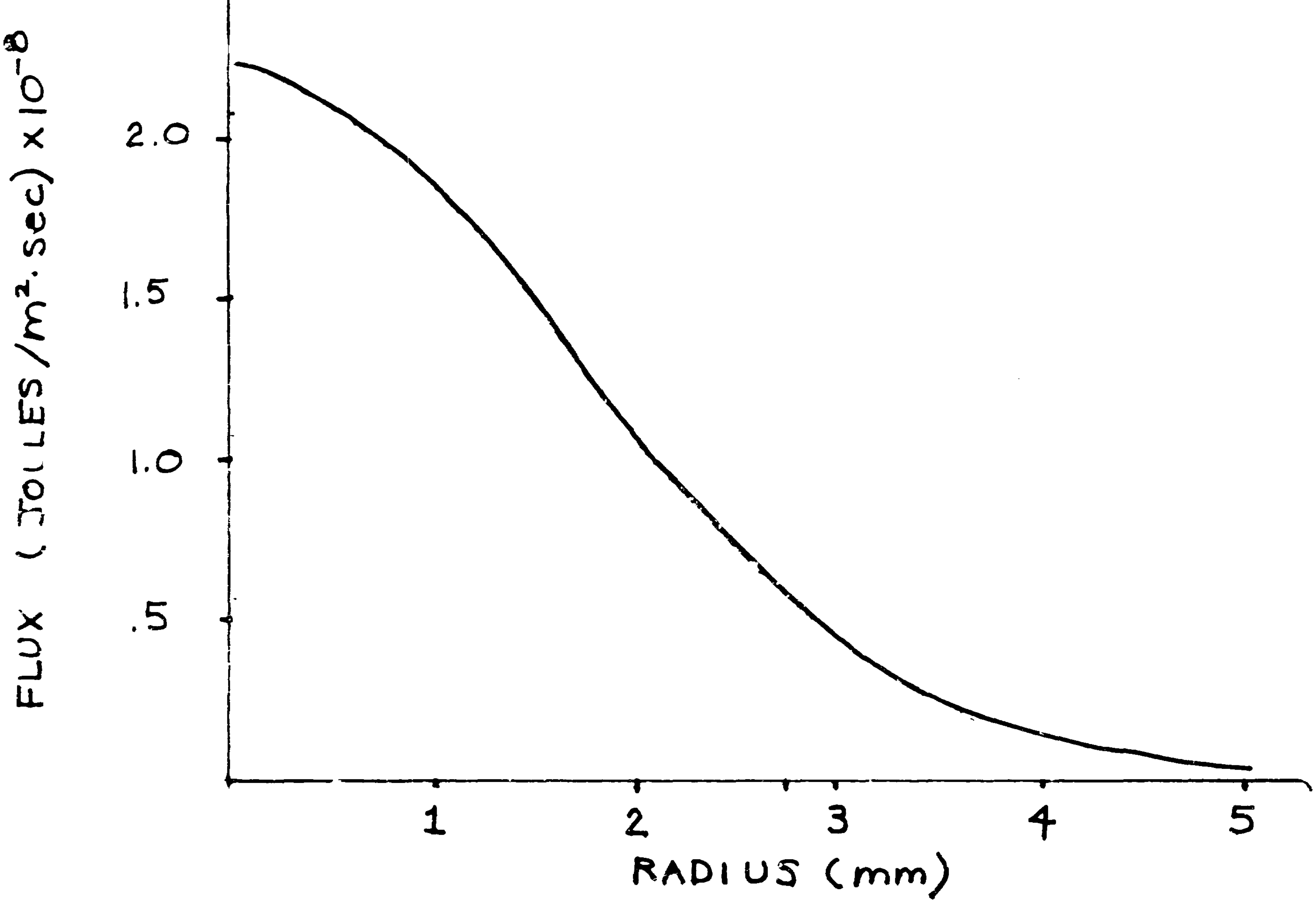


FIGURE 3
HEAT FLUX SCALE FACTOR

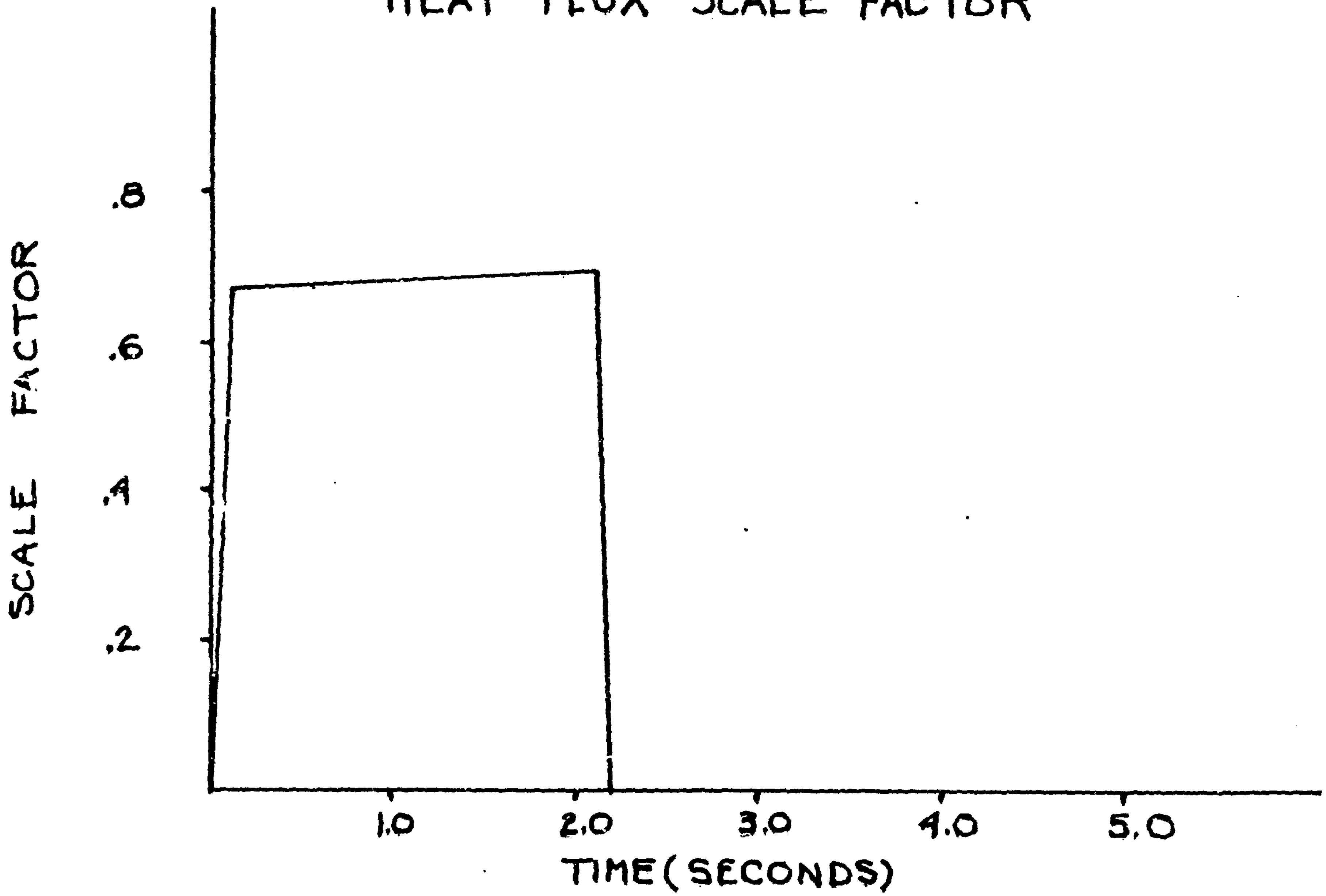
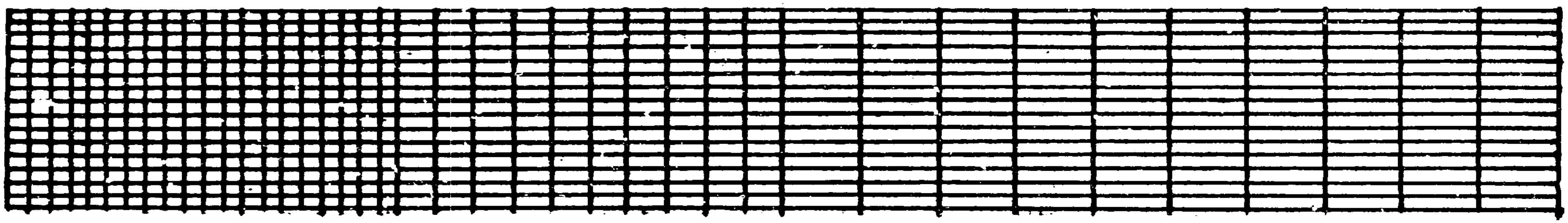


FIGURE 4 FINITE ELEMENT MESH



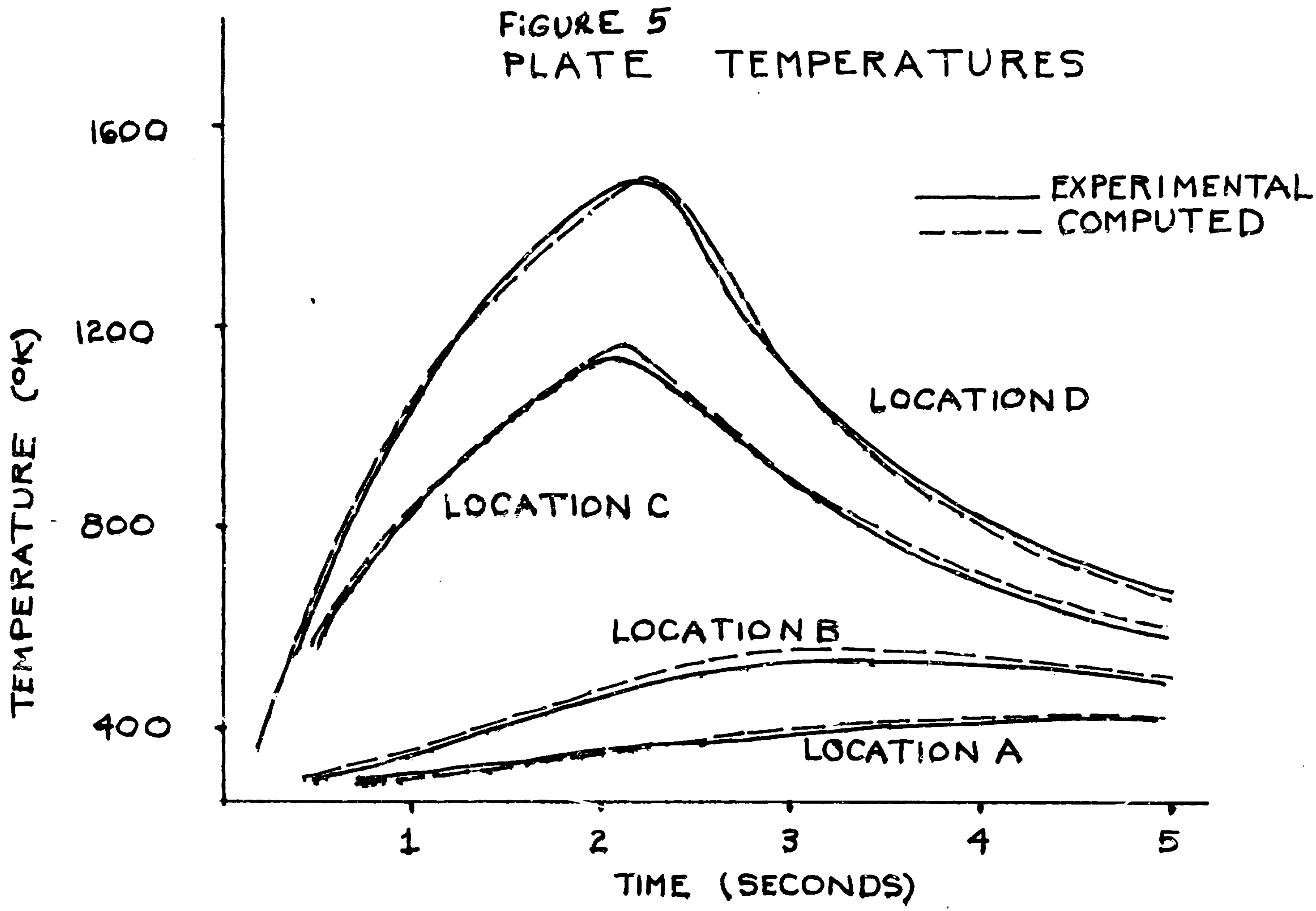


FIGURE 5
PLATE TEMPERATURES
1600
1200
800
400
TEMPERATURE (°K)
EXPERIMENTAL
COMPUTED
LOCATION D
LOCATION C
LOCATION B
LOCATION A
1
2
3
4
5
TIME (SECONDS)

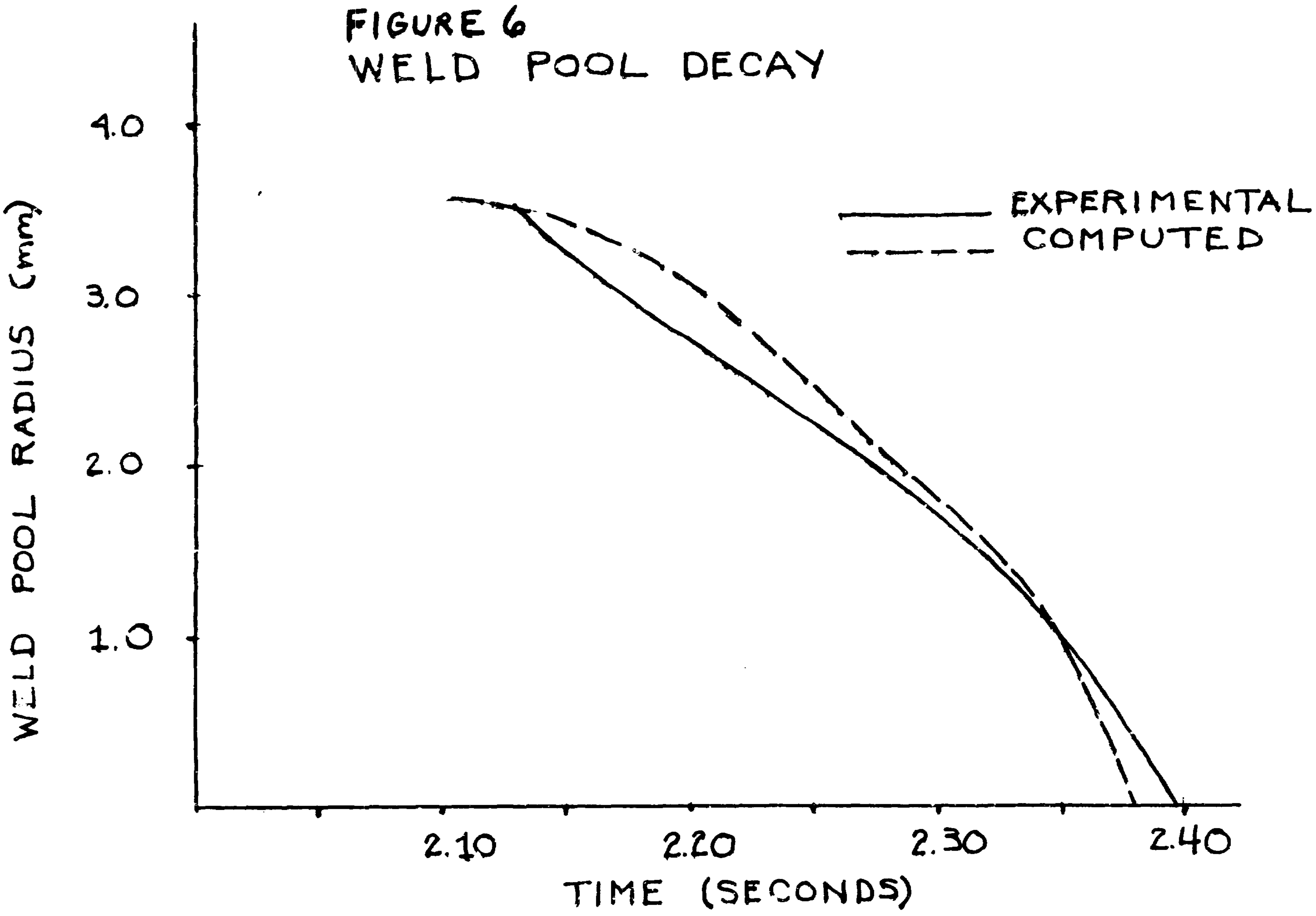


FIGURE 6
WELD POOL DECAY
4.0
3.0
2.0
1.0
WELD POOL RADIUS (mm)
EXPERIMENTAL
COMPUTED
2.10
2.20
2.30
2.40
TIME (SECONDS)

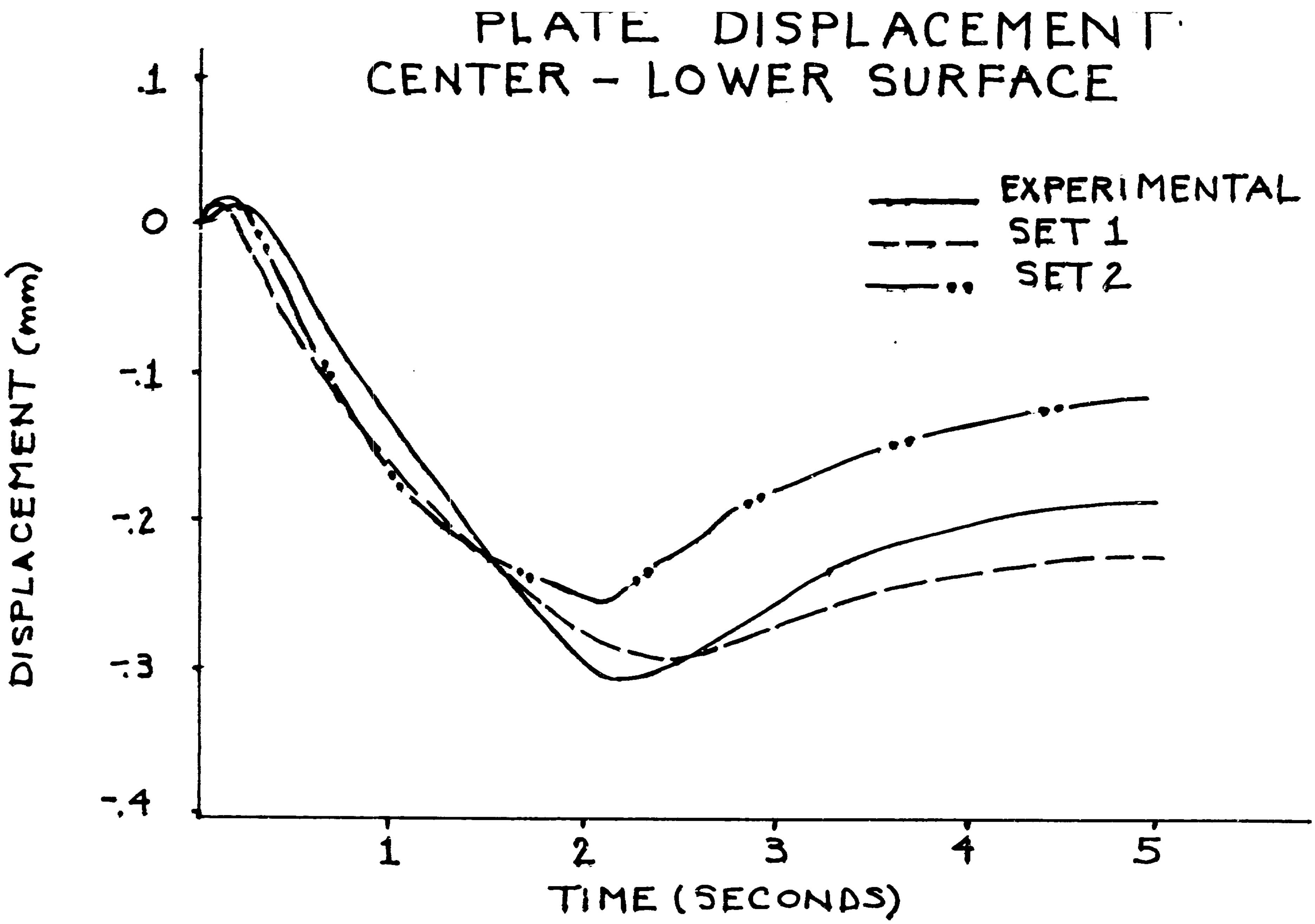
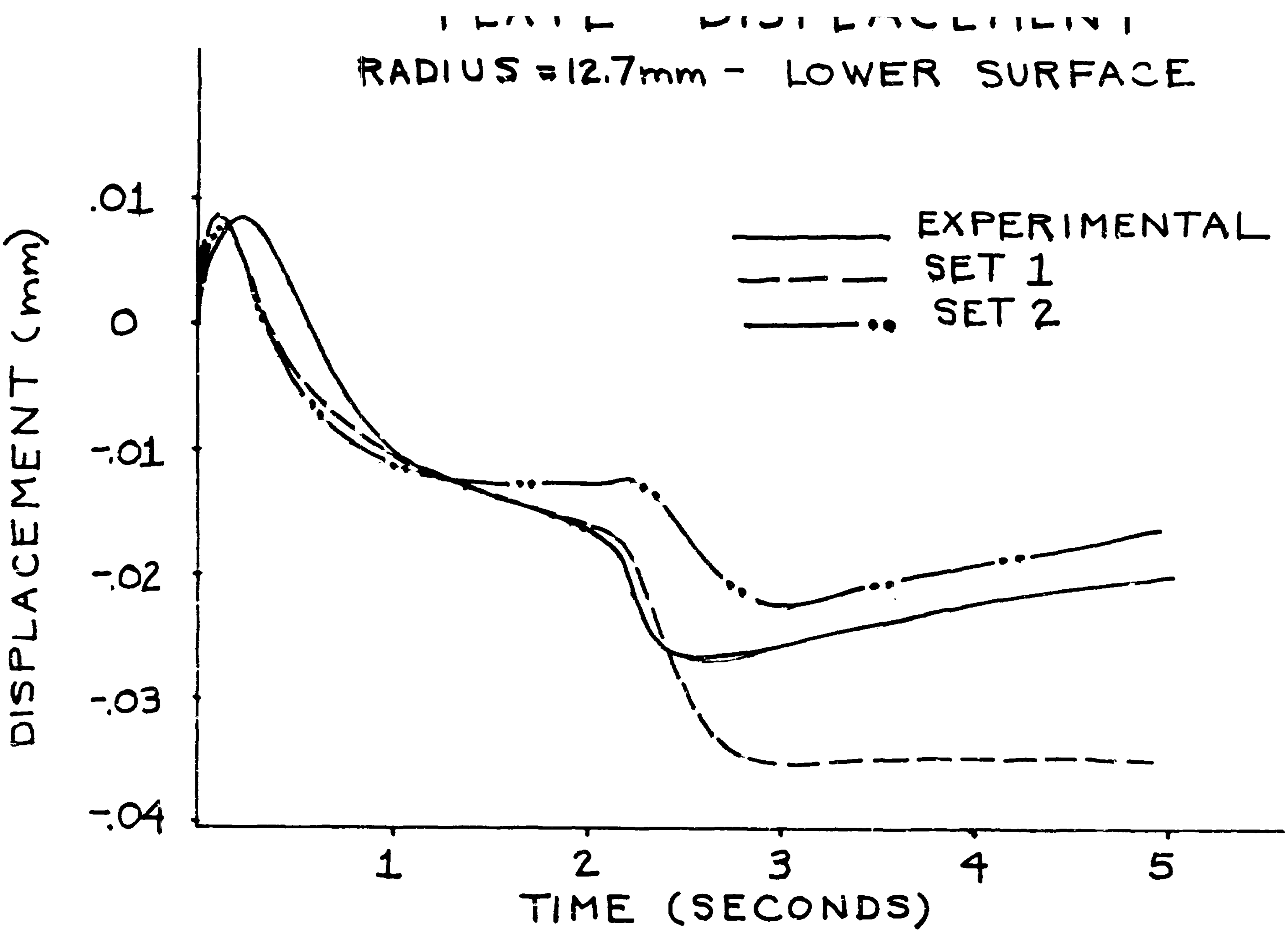


PLATE DISPLACEMENT
CENTER - LOWER SURFACE
EXPERIMENTAL
SET 1
SET 2
DISPLACEMENT (mm)
.1
0
-.1
-.2
-.3
-.4
1
2
3
4
5
TIME (SECONDS)


RADIUS = 12.7mm - LOWER SURFACE
EXPERIMENTAL
SET 1
SET 2
DISPLACEMENT (mm)
.01
0
-.01
-.02
-.03
-.04
1
2
3
4
5
TIME (SECONDS)

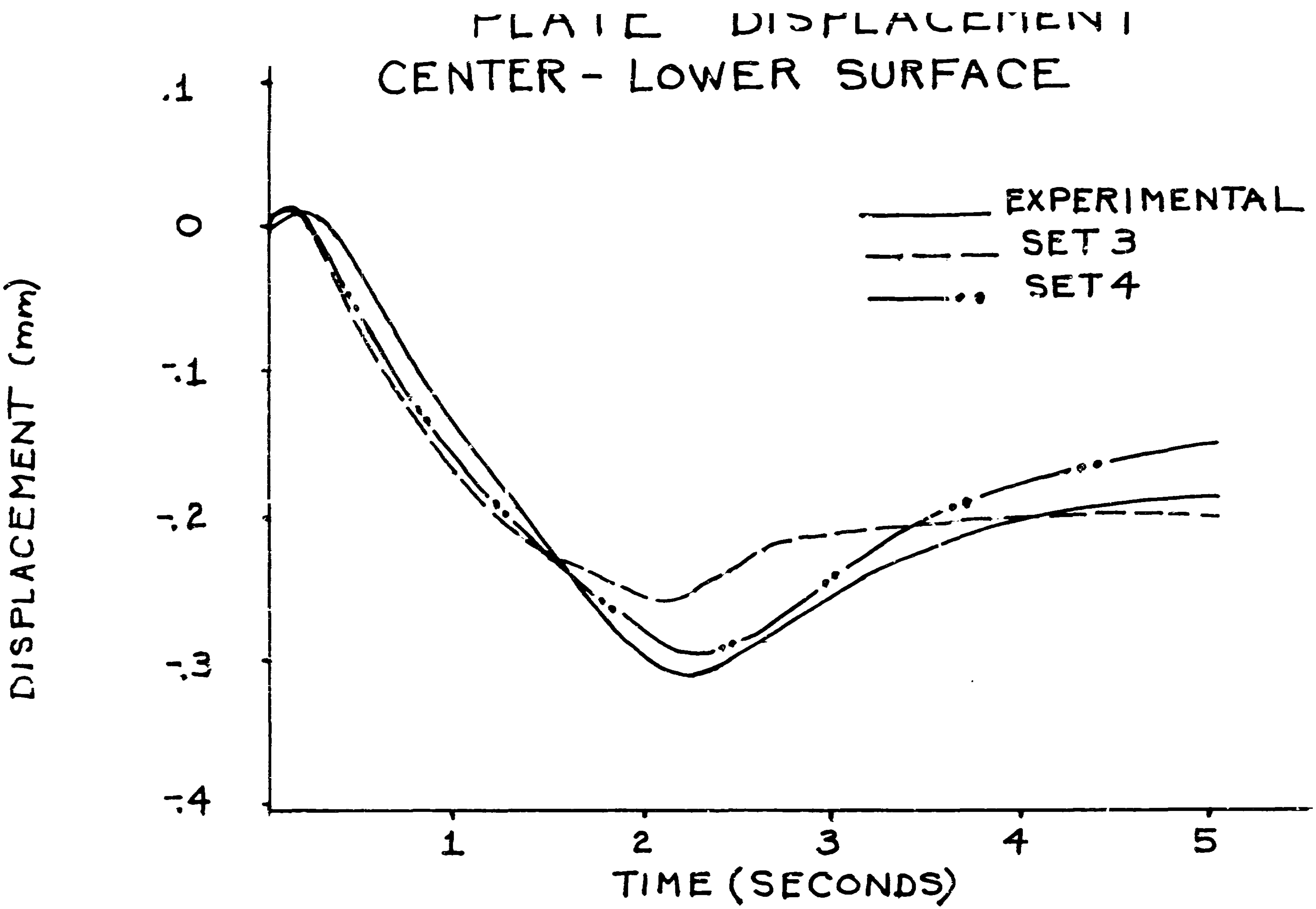


PLATE DISPLACEMENT
CENTER - LOWER SURFACE
EXPERIMENTAL
SET 3
SET 4
DISPLACEMENT (mm)
.1
0
-.1
-.2
-.3
-.4
1
2
3
4
5
TIME (SECONDS)

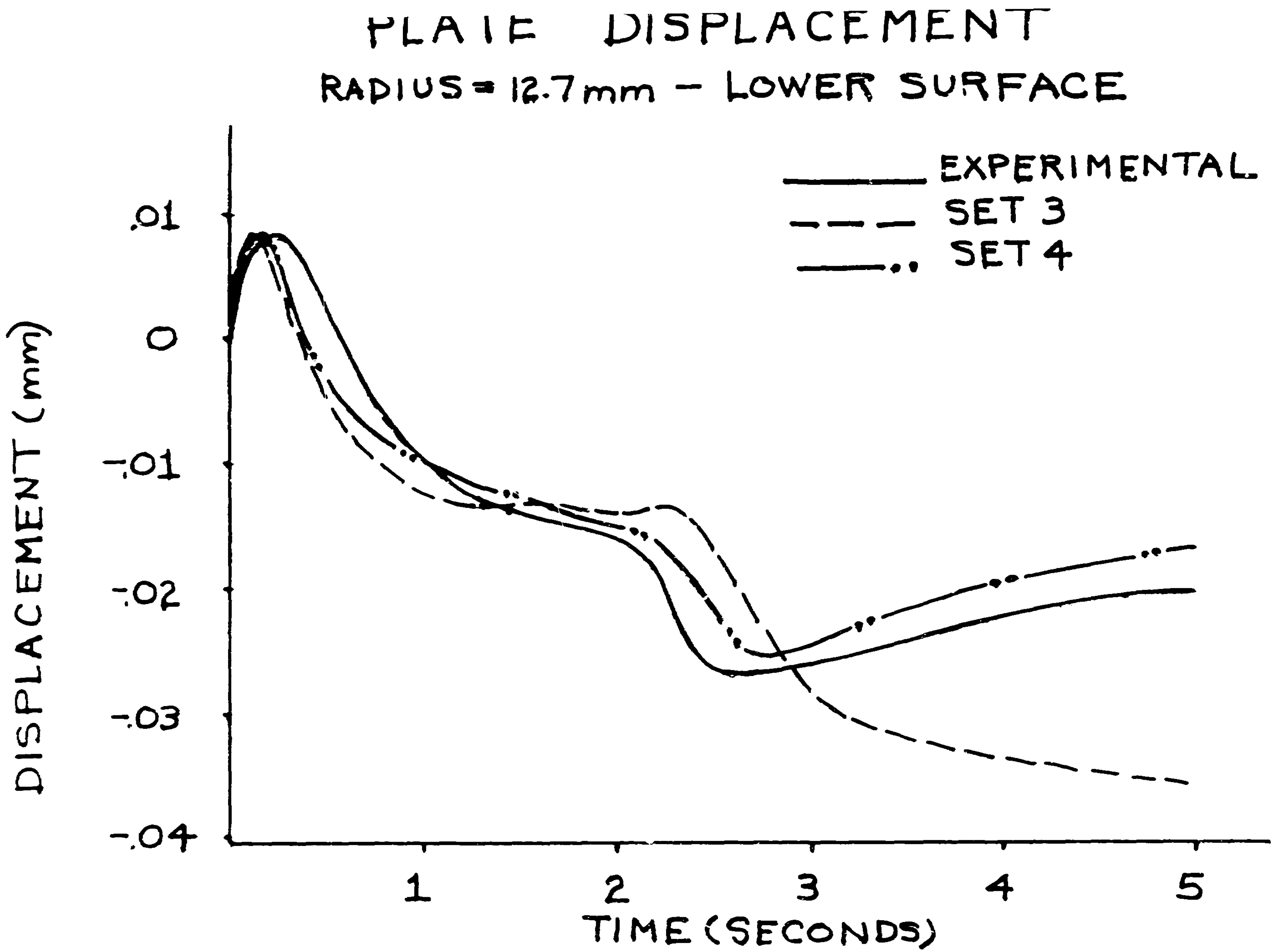


PLATE DISPLACEMENT
RADIUS = 12.7mm - LOWER SURFACE
EXPERIMENTAL
SET 3
SET 4
DISPLACEMENT (mm)
.01
0
-.01
-.02
-.03
-.04
1
2
3
4
5
TIME (SECONDS)